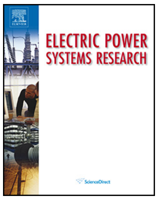
Electric Power Systems Research 132 (2016) 125–131

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



An optimization-oriented sizing model for brushless doubly fed reluctance machines: Development and experimental validation

Tiago Staudt[a,b,*], Frederic Wurtz[a], Laurent Gerbaud[a], Nelson Jhoe Batistela[b], Patrick Kuo-Peng[b]

[a] Univ. Grenoble Alpes, G2Elab-CNRS, F-38000 Grenoble, France
[b] Federal University of Santa Catarina, Grucad, Florianopolis, Brazil

ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 25 October 2015
Accepted 27 October 2015
Available online 31 December 2015

Keywords:
Electromagnetic modeling
Brushless machines
Analytical modeling
Design optimization
Finite element method
Wind energy

ABSTRACT

This paper deals with the electromagnetic modeling and design aspects of brushless doubly fed reluctance machines (BDFRM). It presents the development and the experimental validation of a semi-analytical model (SAM) used for sizing new machine designs. The SAM is an optimization-oriented model implemented using analytical approaches and a deterministic optimization algorithm to find an optimal machine by solving iteratively an objective function, whereas satisfying several output constraints simultaneously. It is fast and accurate for pre-design stages, premises that are confirmed by both simulation and experimental results.

1. Introduction

1.1. The BDFRM in the context of wind power

In wind power applications (WPA), the Doubly Fed Induction Generator (DFIG) is usually the preferred solution because it allows the use of a fractionally rated power converter reducing the overall system cost [1–4]. However, the DFIG has a major drawback that is the use of brushes and slip-rings to connect the rotor windings to the machine-side converter causing reliability problems and increasing operation costs. Among the alternative generators for WPA, the Brushless Doubly Fed Machine (BDFM) has been extensively researched. They keep the advantage of using a reduced scale static converter, whereas they do not have brushes and slip rings, resulting in a mechanically robust topology. They may be of induction (BDFIM) or reluctance (BDFRM) type [2,5] and the paper focuses on the modeling, design and optimization of the Brushless Doubly Fed *Reluctance* Machines (BDFRM). Fig. 1 shows the topology of wind generation system using a BDFRM.

One criticism over the BDFRM is the inherent high leakage flux due to the lower coupling between the windings resulting from the flux modulation process by the rotor. This possibly leads to a reduced power factor (PF) and lower torque density when compared to more traditional electrical machines [2]. Some authors [6,7,1], however, claim that it can produce a high torque density if *optimally* designed. Moreover, the larger leakage reactance characteristic can also be thought as an advantage, since it tends to limit the transient currents, offering a superior low-voltage ride through (LVRT) capability when compared to the DFIG [8,9].

1.2. BDFRM design complexity

The BDFRM is a complex machine to design. The electromagnetic field interaction necessary for torque production limits the use of traditional machine analysis equations and requires the consideration of the associated phenomena simultaneously. Schulz et al. [7], for example, highlight the need of a global optimization rather than local calculations and mention the fact that the "design and optimization of the BDFRM requires radically different techniques to other machines". Xu et al. [6] affirm that the researches about the BDFRM in the recent years have shown "a series of fundamental issues and challenges with respect to the design and control of this machine".

Regarding the BDFRM electromagnetic design, many papers have been recently published contributing on this topic, for exam-

---

* Corresponding author at: Federal University of Santa Catarina, Grucad, Florianopolis, Brazil. Tel.: +55 48 3721 9649; fax: +55 48 3234 3790.
E-mail addresses: tiagostaudt@gmail.com (T. Staudt), frederic.wurtz@g2elab.grenoble-inp.fr (F. Wurtz), laurent.gerbaud@g2elab.grenoble-inp.fr (L. Gerbaud), jhoe.batistela@ufsc.br (N.J. Batistela), patrick.kuo.peng@ufsc.br (P. Kuo-Peng).

http://dx.doi.org/10.1016/j.epsr.2015.10.029
0378-7796/

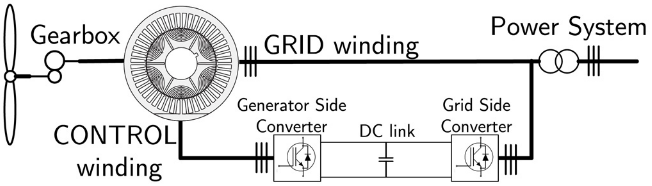


Fig. 1. Topology of a wind power generation system with a BDFRM.

ple [10,1,6]. Despite these works have presented advances, there is not a definition of design guidelines in the literature to size new machines. Aiming to contribute on filling this gap, the paper discusses a BDFRM design methodology that uses optimization algorithms and three distinct modeling levels to refine machine design and define an optimal solution.

2. Propose design procedure

2.1. General approach

The paper proposes to use optimization-oriented models with different properties regarding their accuracy, computation time and ability to deal with many constraints (e.g. dimensions, volume, mass, current densities, inductions in the magnetic circuit, performance parameters such as voltages, power, torque and many others). Each model is dedicated to a specific design stage and they allow to define constrained inputs and outputs for the optimization problem, representing the specifications of the studied application. The best solution that satisfies the constraints is found by the optimization algorithm iteratively while solving an objective function. In [11], the authors introduce this methodology focusing on the optimization problem setting. Here, the paper discusses exclusively the development and experimental validation of the semi-analytical model (SAM) and, therefore, it is complementary to the one in [11].

2.2. Definition of the three modeling levels

The three modeling levels for the BDFRM design are depicted in Fig. 2.

Initially, the machine parameters that will not be optimized such as the number of poles of control (P_c) and grid (P_g) windings, as well as the number of stator (Nsl) and rotor ($Nslr$) slots, are set to define the BDFRM topology.

Then, the semi-analytical model is used to define an initial design from only a few available specifications (e.g. power, terminal voltage and speed). When designing a new machine, there is nearly no information on how the machine will be like and the number of unknown parameters is huge. One of the SAM goals is to reduce the number of uncertainties that permits to increase the model complexity for further refinements. It is computationally very fast and allows testing many design variations and constraints.

The intermediary modeling step uses a Multi-Static Reluctance Network model (MSRN). It uses a discretized domain (much coarser than FEA) and reaches typically a very good trade-off between precision and computation time. It takes into account magnetic material non-linearities and also rotor movement effects (e.g. torque ripple and voltage harmonics) by executing multi-static calculations.

The Finite Element Analysis (FEA) is used to verify SAM and MSRN models since it is a very accurate model. FEA is not recommended in early design stages because most often the number of unknown parameters (from some hundreds up to some thousands of constraints) is huge. If one is interested in testing distinct solutions by checking all possibilities on the constrained search space, using FEA is simply prohibitive from a computational point of view. FEA is more useful in final design stages to further refine the machine topology with just a few constraints (e.g. less than 10). One example of using FEA for that end can be found in [12].

2.3. Definition of the optimization algorithm

Regarding the optimization algorithm, the deterministic Sequential Quadratic Programming (SQP) has been chosen because of the possibility to manage tens, hundreds or even thousands of unknown parameters in a constrained output problem. This would be prohibitive from a computational point of view with, for example, stochastic methods such as the genetic algorithm approach.

The coupling of sizing models to SQP algorithm requires the computation of their Jacobian matrix. Since they are based on analytical and implicit equations, it is possible to exactly determine their partial derivatives [13]. In this work, the analytical equations describing SAM have been implemented in CADES [14] that automatically generates the model gradients.

3. Theory background and the choice of the BDFRM topology

3.1. BDFRM electromagnetic working principles

The working principles of the BDFRM have been presented in [15–17] and their references. This unconventional machine has two sets of three phase windings with different pole numbers and exciting frequencies. To obtain torque, there is a coupling condition given by:

$$P_r = \frac{|P_g \pm P_c|}{2} \tag{1}$$

where P generically refers to pole numbers and indexes g, c and r to grid, control and rotor quantities, respectively. Only the sum (+) case will be considered.

Assuming that the grid winding frequency is fixed, since it is directly connected to the power system, the inverter-fed winding frequency must satisfy a synchronizing requirement given by:

$$\omega_{rm} = \frac{\omega_g + \omega_c}{P_r} \tag{2}$$

where ω is the angular velocity in rad/s.

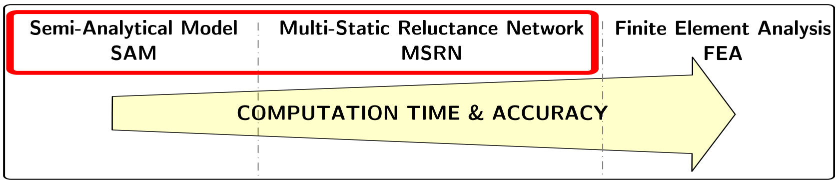


Fig. 2. Proposed three modeling levels approach.